Three-nucleon force effects in proton-deuteron break-up studied with BINA at 135 MeV

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6. Summary and conclusions

In the past two decades, several high-quality NN potentials have been developed such as NijmI, NijmII [5], CD-Bonn [28], and Argonne-V_{18} [32]. These potentials have been fitted with ≈ 40 parameters to the world NN scattering data-base up to energies of 350 MeV and are able to describe NN scattering observables with an excellent precision. In general, the potentials were developed based on phenomenology and by a long-range one-pion-exchange mechanism as proposed by Yukawa. Only recently have NN potentials become available which are systematically constructed based on a low-energy expansion of the fundamental theory of QCD. At low energies these systematic approaches look very promising, however, their application for higher energies, such as discussed in this thesis, still has to be evaluated in more detail.

The high-quality phenomenologically driven NN potentials describe the phenomena involving two nucleons very well. However, exact calculations for systems consisting of more than two nucleons and based on these NN potentials alone fail to describe the experimental data. One of the best known discrepancies is observed in the binding energy of light nuclei. Here, a Green's function Monte-Carlo calculation based on the Argonne-V_{18} NN potential [32] clearly underestimates the experimental binding energies. The missing ingredient is often referred to as a three-nucleon potential (3NP), the existence of which is supported by meson-exchange and quantum-field theoretical approaches.

Also the need for an additional 3NP became clear through studying three-nucleon scattering processes. A first hint came from the differential cross section of the $\vec{p}+d$ elastic reaction [73] that showed the necessity for the inclusion of 3NPs in the NN potentials. Meanwhile, several proposals for 3NPs have been made, such as a dynamic Δ [48] and the Tucson-Melbourne 3NP [40], and these have been embedded within rigorous calculations using of the Faddeev-type equations by, for example, the Bochum-Krakow and Hannover-Lisbon theory groups. More details can be found in Sect. 2.3.

In 1998 a program started at KVI to study systematically 3NP effects in three-nucleon scattering processes at intermediate energies. The first experiments were performed in the proton-deuteron elastic scattering process exploiting the Big-Bite Spectrometer (BBS) and the In-Beam polarimeter (IBP). The data, cross sections and analyzing powers [9, 10, 11, 14, 74] show systematically increasing differences as a function of beam energy from Faddeev calculations solely based on NN potentials. Unfortunately, the inclusion of 3NPs only partly remedies these deficiencies. Furthermore, 3NP effects were studied in the proton-deuteron break-up reaction. This channel allows a more detailed study of these effects because of its very rich kinematical phase space. In particular, the sensitivity to 3NP and other effects, such as relativity and Coulomb, varies significantly throughout the phase space, which, therefore, makes it an ideal system to study 3NP effects in great detail. These studies were initiated at KVI by the KVI-Krakow-Katowice collaboration using SALAD. Meanwhile, cross sections and tensor-analyzing powers of the $\vec{d}+p \rightarrow p+p+n$ have been published in Refs. [21, 22, 23, 75, 24]. It was demonstrated that high-precision data in the break-up channel can be obtained using a large acceptance detection system with a moderate energy resolution. The contribution of 3NP effects was found to be present, albeit relatively small.

In 2004, the next generation of break-up measurements were carried out using a new detection system, carrying the name BINA. BINA, as a successor of SALAD, inherits parts of its features from its predecessor. It is composed of a forward wall which detects forward-scattered particles between $10° - 35°$ and a backward-ball which covers the rest of the scattering angles up to $165°$. The azimuthal angle coverage for this θ-range is almost complete. With this, BINA covers almost the entire kinematical phase space of the break-up reaction. The full azimuthal angle is essential for the extraction of polarization observables.

Inspired by the first break-up results obtained with SALAD, various break-up experiments at several beam energies were performed with BINA in the past few years. The first experiment with BINA was performed in 2005 with a polarized proton beam of 190 MeV. This energy is about three times larger than the energy used for the first break-up experiment with SALAD. The main motivation was to expand the data-base for cross sections and polarization observables to higher energies with a larger sensitivity to effects such as those coming from 3NP. The results of that experiment are reported in the thesis of Hossein Mardanpour [27] and will soon be published. Intriguingly, a huge discrepancy with the state-of-the art calculations, independent on S, was observed for the vector analyzing power of the proton in the case of very small relative azimuthal angle between the two final-state protons. The deficiency increases even further when a 3NP was added. Furthermore, in various parts of the phase space, the differential cross section could also not be explained by the calculations. Part of the discrepancies could be accounted for by relativistic effects. Motivated by the observations at 190 MeV and to cover the gap in the data-base between the two beam energies (65 and 190 MeV/nucleon), the $\vec{p}+d \rightarrow p+p+n$ reaction was studied with a proton beam at energy of 135 MeV using BINA in 2006. The results of this more recent experiment are the subject of this thesis.

The $\vec{p}+d$ break-up reaction was studied using a polarized beam of protons impinging on a liquid deuterium target which was located at the center of BINA. The polarized beam was prepared by POLIS and accelerated by AGOR to an energy of 135 MeV. The break-up reaction has been identified nearly background free and kinematically complete by measuring the scattering angles and energies of the two final-state protons. Our main priority was to study configurations in which both protons scatter to polar angles smaller than $30°$ and with a relative azimuthal opening angle varying between $20°$ and $180°$. Differential cross sections and analyzing powers have successfully been measured and are presented as a function of S for different combinations of $(\theta_1, \theta_2, \phi_{12})$. The results are depicted in Figs. 5.1-5.10.

For most of the configurations at large azimuthal opening angle, $\phi_{12} \geq 100°$, and taking the systematic uncertainties into account, a reasonable agreement has been observed between the cross-section data and the corresponding theoretical predictions. Only for the configuration (θ_1=28°, θ_2=28°), a large discrepancy was observed between data and theoretical predictions at large relative azimuthal opening angles. However, the calculation, which is based on the extended CD-Bonn potential with a dynamic Δ and with Coulomb corrections, CDB+Δ+Coulomb, shows a larger discrepancy with the data than the other calculations. This could hint at the importance of short-range 3NP effects which are not included in the present 3NP models.

For configurations with a small relative azimuthal angle, the picture changes. Here, the measured cross sections show a large discrepancy with a calculation which includes the TM' 3NP. In this region, the CDB+Δ+Coulomb calculation has a smaller deficiency when compared with the experimental data, but the deficiency is still large for small values of polar angles as shown in Fig. 5.12. Specifically, for $\phi_{12} = 20°$ this calculation removes the deficiencies between the data and the calculations. For some of the configurations at small relative azimuthal opening angles, the Coulomb force significantly influences the cross section as illustrated in Fig. 5.13. Here, the data clearly support a calculation which accounts for the Coulomb effect.

For the analyzing powers, the major discrepancies between the data and the theoretical calculations arise at small azimuthal opening angles. In this range, the predictions based solely on a NN potential are closest to the data, although, the disagreement is still significant. The inclusion of 3NPs increases the gap between data and predictions as can be seen from Fig. 5.12. The contribution of the TM' 3NP appears to be larger than the implicit inclusion of the Δ resonance by the Hannover-Lisbon theory group. It is interesting to note that a similar, but even larger, discrepancy has been observed in a break-up study at an incident beam energy of 190 MeV. The effects of the Coulomb force and higher-order relativistic effects are generally predicted to be very small for the analyzing power as shown in Fig. 5.14. Therefore, the origin of this discrepancy must lie in the treatment of 3NPs.

In general, the state-of-the art calculations describe reasonably well the experimental break-up data taking into account its precision. However, we still observe significant discrepancies at some parts of the kinematical phase space. In particular, predictions for the analyzing powers show a systematic deficiency at small relative azimuthal opening angles, which corresponds to small relative energies. Since the vector analyzing power is, in general, not sensitive to Coulomb and higher-order relativistic effects, we suspect that this discrepancy stems from 3NP effects which are not included in the present models. Possibly, the modeling of short-range 3NP can be significantly improved, for which the data presented in this thesis can be used as a test bench.

In this experiment the entire phase space of the $\vec{p} + d$ break-up reaction has been measured using BINA. However, due to lack of time, we analyzed only part of the data for which the two protons are detected in the forward wall of BINA. This corresponds to scattering angles smaller than 30° and covers the complete azimuthal angle. The cross sections for most parts of the phase space are large. Therefore, it is feasible to extend this study by analyzing the data for other configurations as well. In particular, the phase space for which one proton scatters to the forward wall and the second proton scatters to the backward ball, should be feasible to study, although the angular resolution of the backward ball is worse than that of the forward wall.

The systematic study of the elastic-scattering cross sections as a function of beam energy shows that by increasing the beam energy, differences between data and state-of-the art Faddeev calculations including modern NN and 3N potentials increase [11]. A similar observation has now been made for the break-up reaction. The $\vec{d}+p$ break-up measurement at 65 MeV/nucleon revealed that the data cannot be described by calculations based on two-nucleon potentials alone, and therefore, demonstrated the need to include 3NP effects. Most of the discrepancies were resolved by including a 3NP in the Faddeev framework. In the $\vec{p} + d$ break-up experiment at 190 MeV, much larger discrepancies were observed with predictions based on NN potentials and NN+3N potentials [27]. Surprisingly, these discrepancies could not be resolved by including a 3NP. With the results of the experiment presented in this thesis, we extended these studies by performing a measurement at intermediate energies, e.g. 135 MeV. Also here, discrepancies were found which could not be resolved by adding a 3NP. However, the size and location of these deficiencies differ with energy, which makes the various studies taken at different incident beam energies very valuable. To understand unambiguously the nature and details of 3NP effects, it is mandatory to interpret simultaneously all available break-up and elastic-scattering data taken at different beam energies with respect to Faddeev calculations incorporating high-quality NN and 3N potentials, the Coulomb force, and relativistic effects.